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SYSTEMS ENGINEERING AND THE USER: INCORPORATION OF USER REQUIREMENTS INTO THE SE PROCESS

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A scientific mission goes through two distinct stages, each with its own special requirements for systems engineering. A division director at NASA Headquarters, assisted by a program chief and a program manager, conducts the first stage. These three people, assisted by committees and working groups, define the mission, formulate its objectives, establish its rough boundaries and manage the selection of the experiments. The division director practices a rough and ready kind of systems engineering, balancing the desire of the scientist for the most complex sophisticated instrument possible against the desire of the Office of Management and Budget and Congress to reduce the NASA budget. If the division director's systems engineering is done well, the mission will be supported and scientific results obtained. If, on the other hand, the systems engineering is poor, the mission may be canceled either because the scientific community concludes the scientific objectives do not merit the cost or because the Office of Management and Budget or Congress thinks the cost is too high.

After the experiments have been selected, the action shifts from Headquarters to one of the NASA Centers, and the second stage begins. A project manager, assisted by a project scientist and supported by an engineering and a financial staff, is in charge of the second stage. The second stage begins with the preliminary design phase and ends when the last scientific paper has been published. All the hardware for the mission is constructed, tested and operated in the second stage.

Systems engineers incorporate the scientists and their instruments into the systems engineering process during the preliminary design phase. At the conclusion of the preliminary design phase, the project manager conducts a preliminary design review to

assure everyone—the scientists, the project management, the Center management and NASA Headquarters—the scientific objectives and requirements have been incorporated into the systems engineering process.

This paper is organized into four parts. In the Gestation Phase, I describe the process of starting a new mission and establishing its rough boundaries. Next I show how the scientific experiments are selected. Then we enter the Preliminary Design Phase, where we incorporate the scientist's instruments into the systems engineering process. Finally, I show how the Preliminary Design Review (PDR) assures NASA management and the scientists that the scientific requirements have been incorporated into the systems engineering process to everyone's satisfaction.

Throughout I emphasize the dual role of servant and master that the systems engineer plays with respect to the scientist and the project manager. As servant, the systems engineer works to assure the scientists that the project will meet the requirements of their experiment and their instrument; as master, the systems engineer works to assure the project manager that the scientists and their instrument will meet the requirements of the project. A glossary of terms appears at the end of this paper.

I emphasize the need for the systems engineering process to consider all of the pieces of hardware that the mission will require and all the activities that must be conducted during the entire mission. It is easy, in the early phases of a mission, to focus on the spacecraft and the instruments and to ignore or push into the background those activities and facilities that will be needed later or are the responsibility of other offices. The associate administrator for the Office of Space Science and Applications needs to know, before committing to undertake a mission, that the

entire mission has been thought through, that the facilities will be available, and that the funding is adequate to procure all the flight and ground-based hardware and to pay for all the work that will be required.

I arbitrarily end this paper with the PDR. Clearly there will be continuous interaction between the scientists and the systems engineers throughout the remainder of the mission. However, the main purpose of the PDR is to see that the user requirements have been properly incorporated into the system. Other papers discuss the role of systems engineers in later phases of the mission.

THE GESTATION PHASE

If we are to successfully incorporate user requirements into the systems engineering process, we need to know how NASA creates a new mission and establishes its principal boundaries; we need to know who selects the scientific instruments and when.

New missions get started in a variety of ways. A person with a new idea may initiate a new space mission. A scientist at a NASA Center or a university may make a discovery, ask a new question or invent a new instrument. An engineer at a NASA Center or in industry may invent a new control system enabling more precise measurements to be made. A technology may mature.

New missions have been started this way in the past, but now, more and more, new missions either come from a group of people convened by NASA specifically to think about new missions or are logical follow-ons to existing or completed missions. The Hubble Space Telescope was started as a logical step after the Orbiting Astronomical Observatories. Its scientific objectives were laid down in 1964 during a summer study conducted for NASA by the National Academy of Sciences Space Science Board. The Advanced X-Ray Astronomical Facility continues the x-ray observations begun with Uhuru and High Energy Astronomy Observatory. Ulysses continues the study of the

Sun begun by HELIOS. Some missions are precursors to later more complex missions. Surveyor and the Lunar Orbiter were precursors to Apollo. The Lunar Observer and the Mars Observer, in addition to increasing our knowledge of the Moon and Mars, will be designed to provide data needed to design manned lunar bases and manned missions to Mars.

Applications missions result from a need for additional coverage, better resolution, more complete coverage of the electromagnetic spectrum or a new operational spacecraft.

Although there is no set process by which a new mission gets started, once it begins, there is a fairly predictable process by which it moves from concept to design to flight. Usually a new mission gets underway when a dedicated advocate devotes the time and energy required to get the idea accepted within NASA. This advocate may be located at a Center, a university, another federal agency, an aerospace company or in NASA Headquarters. The advocate prepares a rough design of the spacecraft and a list of potential instruments. With these in hand, the advocate buttonholes scientists, engineers, Center and Headquarters personnel to persuade them to become supporters of the mission. At a Center, the advocate may bootleg some feasibility studies at the Center before taking the concept to Headquarters. At some point, the advocate must describe the mission to the director of the appropriate division in NASA Headquarters and persuade the director that NASA should undertake the mission. If it is an astronomy mission, the advocate must convince the director of the Astrophysics Division; if a planetary mission, the director of the Solar System Exploration Division; if an Earth science or applications mission, the director of the Earth Science and Applications Division. The director may ask the advocate and supporters to describe the concept to the appropriate NASA advisory committee or to a summer study sponsored by the Space

Science Board. The director may ask a Center or a contractor to make a feasibility study of the mission before committing to the 5- or 10-year effort that is required to get a new mission underway. The advocate may appeal to the associate administrator for the Office of Science and Applications to tell a reluctant division director to undertake the mission, but until the director is convinced that the mission is worth doing, it is almost impossible to get a new mission started.

Once the division director becomes enthusiastic about the mission, it will be incorporated into the director's long-range plan, and the groundwork will be prepared for approval by NASA senior management, Office of Management and Budget and Congress. Once the division director includes a description of the mission in the division's advanced program, the advocate's work is over; the mission takes on a life of its own. The division director provides funds for studies and for research and development and may provide funds to several scientists to begin work on potential instruments for the mission.

Applications missions are started by an agreement between the division director at NASA Headquarters and the division director's counterpart at the National Oceanic and Atmospheric Administration, or whichever agency needs the mission. They agree that the mission has merit and that they should begin to jointly plan for the mission. Agreements are made as to what research and development will be conducted, who will conduct it, and which agency will pay for it. They will produce a mutually acceptable plan of action by which they will seek approval and funds.

SETTING THE BOUNDARIES

The scientific or applications objectives establish some but not all of the boundaries of a space mission. Other factors, such as the kind of transportation or the funds available help set the boundaries. Nonscientific criteria may have influenced the scientific

objectives themselves. The initial diameter of the Hubble Telescope, four meters, was chosen in the mid-sixties because that was the diameter of the largest spacecraft that could be put inside the shroud of the Saturn V launch vehicle. Later, the diameter was reduced to 3.2 meters to take advantage of existing manufacturing, test and calibration equipment. The broad boundaries of the Viking mission were set by the capability of the Titan launch vehicle. As a matter of fact, in its formative stage, Viking was called the Titan Orbiter-Lander Mission. An earlier Mars orbiter-lander mission, Voyager, had been planned for a Saturn V; this big Voyager was canceled by Congress because it was too large and too expensive and because the scientists involved would not support such an expensive mission at that stage in the exploration of Mars. The competition with the Soviets also helped set the boundaries for Viking. The scientific returns from Viking had to be sufficient to justify the cost of the mission, even though the Soviets might land a spacecraft on Mars before Viking got there. National needs—foreign policy, security, development of new technology and the maintenance of an institution or a capability—may influence the size, scale and timing of a mission. For a decade scientists unsuccessfully tried to persuade NASA to start a mission to study the interplanetary medium near the Sun. After President Johnson offered to undertake a joint space mission with Germany, it took NASA just 24 hours to establish the HELIOS Mission to make a close flyby of the sun. The need to test the Titan IIIC launch before the launch of the Viking mission dictated that HELIOS would use the unproven Titan IIIC rather than the existing Atlas-Centaur.

The actions of the members of Congress as they review, authorize and appropriate funds for a mission may help establish the boundaries of a mission. A key chairperson or a powerful committee member may decide that a particular mission is worth \$500 million but not \$750 million; the chairperson

may decide to support a mission if it will increase employment or prevent the closure of a facility in the chairperson's district.

Purists may argue that systems engineering should focus on technical constraints and need not take into account nebulous political and managerial constraints. Unfortunately, such constraints have been with us since the first time two people joined together to accomplish a task neither could do alone. Incorporation of such constraints into the systems engineering process is just as important as incorporating the purely technical constraints. The division director, however, must keep the political and technical constraints separate and should never attempt to justify a political constraint with some flimsy technical justification. If this happens, the rest of the participants in the mission will become confused and the division director will lose credibility. If the participants are kept straight, then later, if relief is needed from some such constraint, the division director will know who must be persuaded to get relief and the kind of justification that must be prepared.

In the early days of NASA, with a powerful administrator and with space exploration a major national goal, a project manager could ignore factors other than the scientific and technical requirements. Today, the assembly and maintenance of the necessary support for the mission are so difficult that these other factors may become as important, if not more important, than the requirements derived from the objectives of the mission.

Out of this combination of political and technical considerations, the major boundaries are set for a mission. The launch vehicle is selected, the project management center is picked, the trajectory and a tentative launch date identified, and a rough idea formed of the kind and number of instruments that will make up the payload. The availability of transportation and the support of the Office of Operations is established. A rough cost estimate is made.

THE ROLE OF THE PAYLOAD AND THE TECHNICAL WORKING GROUPS

As soon as the broad boundaries of a mission are established and the division director is confident about obtaining approval, the groundwork begins for selecting principal investigators—the scientists who will perform the mission experiments. To make the selection, the division director first needs to know how many and what kind of instruments can be placed on the spacecraft, an analysis accomplished by two working groups: a Payload Working Group and a Technical Working Group. The Payload Working Group consists of NASA and academic scientists from the scientific disciplines involved in the mission, and the Technical Working Group of system engineers and discipline engineers representing all the engineering disciplines and subsystems required to design, build and operate the spacecraft. Working together, these two groups will design a trial payload that will accomplish the scientific objectives of the mission and a spacecraft capable of supporting that payload. In this joint activity, we begin to incorporate the user requirements into the systems engineering process.

The trial payload and the spacecraft emerge through an iterative process. The members of the Payload Working Group select a trial payload—a group of instruments that accomplish the objectives of the mission. In assembling this trial payload, the Payload Working Group may invite scientists to come to a meeting to describe instruments they hope to fly on the mission. They may invent new instruments that are needed to accomplish the objectives. The Payload Working Group will estimate the weight, volume, power and communication needs, and specify the orientation and stabilization requirements for each instrument. One or more members of the Technical Working Group will attend the meetings of the Payload Working Group to help them develop the requirements and to design the spacecraft and

bring back to the Technical Working Group a better understanding of the payload that is emerging.

Meanwhile, the Technical Working Group will use the scientific objectives and broad constraints of the mission and design a hypothetical spacecraft for the mission. The Technical Working Group then takes the first trial payload prepared by the Payload Working Group and integrates it into the spacecraft. The two groups then hold a joint session where the Technical Working Group reviews the fit between the payload and the spacecraft, and the descriptions of changes that must be made either in the spacecraft or in the payload to make them compatible. Additional power may be required, the structure of the spacecraft modified, or one or more instruments may have to be redesigned or eliminated. At the conclusion of the joint meeting, the two groups agree on the actions each will take during the next iteration with the mutual objective of making the payload and the spacecraft compatible. The Payload Working Group refines the payload and the Technical Working Group refines the design of the spacecraft. They meet again, review their progress, and decide on the next course of action.

After a year or so of joint effort and two or three such iterations, a spacecraft and a payload will emerge that are satisfactory to both groups, the scientific community, the division director, the program manager, the program scientist and to senior NASA management. The division director and the program scientists are now ready to select the actual scientists, and their instruments, for the mission.

SELECTION OF THE SCIENTIFIC EXPERIMENTS

The associate administrator for the Office of Space Science and Applications selects the scientists who do research in space. The division director, using an ancient procedure established in 1960, is in charge of all the ac-

tivities associated with the selection process. People sometimes ask why the experiments are selected by an official at NASA Headquarters rather than by one at the NASA Center that will manage the project. Others ask, why not use the instruments selected by the Payload Working Group for the trial payload and avoid all the time and energy that goes into the NASA selection process? Why NASA Headquarters, why not the National Academy of Sciences Space Science Board? These are good questions, and in some cases, the answer is easy: the particular method has been tried and found not to work; in others, the answer is not obvious and some explanation is necessary.

History shows that the nation needs a vigorous broad-based space science program that involves many academic scientists. Academic scientists are a fertile source of new ideas, and their involvement rapidly disseminates the knowledge and experience gained in the space program to the next generation of scientists and engineers. In addition, the participation of academic scientists and their graduate students helps assure a continuing supply of space scientists and aerospace engineers. Academic scientists also form a strong, vociferous lobby for the NASA space science program.

History also shows that NASA needs competent, creative scientists at its Centers to help conceive and design new missions and to work with the academic scientists who participate in NASA's missions.

The academic scientists and the NASA scientists at the Centers fiercely compete for the right to conduct investigations on NASA missions. If an official at the Center responsible for the mission selected the principal investigators, then the academic scientists would feel that the Center scientists had an unfair advantage. The NASA scientists would be more familiar with the mission and therefore able to prepare better proposals. In addition, they would be colleagues of the Center people handling the selection. If the Space Science Board, made up entirely of

non-NASA scientists, handled the selection, then the NASA scientists would feel that academic scientists had an unfair advantage. By mutual agreement between NASA and the Academy, NASA scientists cannot serve on the Board because they would be providing advice to themselves.

NASA procedures were formulated to reduce the fears of these two groups of scientists and to encourage them to participate in NASA's space science program. NASA provides a competitive process that assures equal access to NASA's space science missions for all scientists, whether they are at universities, NASA Centers or in industry, and whether they are domestic or foreign scientists. Administrative scientists at NASA Headquarters, who are no longer conducting research and hence have no conflict of interest, conduct the selection process.

The selection process proceeds through three stages. The first stage, the creation of a trial payload and the design of the spacecraft, was discussed above. Next NASA issues an Announcement of Flight Opportunity (AFO) to scientists to inform them that NASA intends to proceed with the mission and invites them to submit a proposal to conduct experiments during the mission. After the proposals are submitted, they are evaluated, and a final selection is made by NASA Headquarters.

THE ANNOUNCEMENT OF FLIGHT OPPORTUNITY

As soon as the division director is reasonably sure that the mission will be approved by NASA senior management and by Congress, he or she will issue an AFO. The AFO specifies the objectives of the mission and invites scientists to propose investigations. It gives the ground rules for the proposals and the deadline for their submission.

The AFO is a very important document. Several (sometimes 100 or more) teams of scientists will spend several months preparing their proposals. Each team consists of

scientists, engineers and financial analysts who use the information in the AFO to prepare the scientific, technical and financial parts of their proposals. Their written proposal is the final and generally the only opportunity they have to persuade NASA to select their experiment. (Sometimes competing scientists are invited to brief the reviewers.) NASA bases its selection on the written proposal. Once the procedure is completed and the experiments are selected, it is almost impossible for a dissatisfied scientist to overturn the decision. Once the selections are made and contracts awarded, the principal investigator's team is legally obligated to produce the instrument, conduct the experiment and publish the results. NASA is legally obligated to provide funds and space on the spacecraft and to conduct flight operations and provide data to the investigator.

Careful preparation of the AFO is essential. Large amounts of time and energy are required to prepare and evaluate the proposals. If the information in the AFO is inadequate or wrong, experimenters may be discouraged from competing, or experimenters with instruments not suitable for the spacecraft may be selected, which can lead to costly overruns or schedule slips.

The preliminary systems engineering done by the Technical Working Group and the Payload Working Group plays a crucial role in the preparation of the AFO. The AFO contains a description of the trial payload and the spacecraft generated by the two working groups. The AFO specifies the subsystems planned for the spacecraft in sufficient detail so that the proposers can design their instruments to function in harmony with subsystems. The AFO must specify any special requirements for the instruments such as the need to keep electromagnetic interference, nuclear radiation levels or outgassing below specified levels. The thermal characteristics of the spacecraft are described, and the thermal specifications that the instruments must meet are included.

The AFO specifies the date the proposals must be returned and in some cases limits the number of pages of a proposal to avoid getting lengthy proposals loaded with extraneous information.

EVALUATING THE PROPOSALS

The scientists send their proposals to the division director at NASA Headquarters who is responsible for the mission. After receipt of all proposals, the division director forms two groups to assist in the evaluation. The first group, chaired by the program scientist, consists of scientists who are peers of those proposing experiments and who will evaluate the scientific and technical merits of the proposals and assign them a priority for inclusion in the mission. This group of scientists must be free of any legal conflict of interest with respect to any of the proposals, which is the reason why they cannot be chosen until all the proposals are in. The second group consists of engineers at the project management Center similar in membership to the Technical Working Group (in many cases it will be the Technical Working Group). This group will examine all the proposals to see if the instruments proposed are compatible with the spacecraft and judge whether the proposer has the team and the facilities required to carry out the investigation.

As soon as the division director has the proposals, copies are sent to both groups. After the two groups complete their work, they send the results of their evaluation to the division director. If an otherwise high priority investigation is incompatible with the spacecraft, the division director may ask the project team to conduct a short study to determine whether the instrument or the spacecraft can be modified to make the two compatible and, if so, to prepare an estimate of the costs involved.

After receiving the evaluation made by the scientific working group and the project team, the division director and the chief

scientists prepare a list of the principal investigators who they think are the best qualified to accomplish the objectives of the mission. Their selection is based on, and must be consistent with, the evaluations of the scientists and the project team. The division director is free to choose between two competing proposals that have been given the same priority by the scientists but is not free to pick a proposal that was given a lower priority. In other words, the division director must select a principal investigator whose proposal was placed in Category I by the scientific working group rather than pick an investigator whose proposal was placed in Category II, even though the Category II experiment might be cheaper or easier to integrate with the spacecraft. The instruments of the principal investigators selected must be certified compatible with the spacecraft or the division director must have the results of a study that shows that the instrument or the mission can be modified to make the instrument compatible. Since each of the investigators selected has proposed a specific instrument, in the process of selecting the investigators the division director has also selected the suite of instruments that will make up the payload for the mission.

After completing the list of principal investigators and the justification for their selection, the division director takes the recommendations to the members of the Space Science Steering Committee for their review and recommendation.

THE ROLE OF THE SPACE SCIENCE STEERING COMMITTEE

The Space Science Steering Committee is composed of the directors and the deputies of each of the program divisions in the Office of Space and Applications. Traditionally, if the director is an engineer, the deputy is a scientist and vice versa. Thus the Space Science Steering Committee consists of roughly equal numbers of scientists and engineers and is capable of reviewing the merits of

investigators, the selection procedure, and all other technical and managerial aspects of the mission. It is chaired by the chief scientists in Office of Space Science and Applications and reports directly to the associate administrator for that Office.

The Space Science Steering Committee reviews the investigations that have been selected and the process by which they were selected. It reviews the investigations for their scientific and technical merit and for their compatibility with the spacecraft. If there are any objections or reservations raised by anyone about the payload, the Space Science Steering Committee reviews those objections. Normally the investigators chosen by the division director are accepted; however, if a member of the Steering Committee objects to a selection or questions the selection process, then the Committee may send the division director back to prepare a different version of the payload.

The Space Science Steering Committee serves as the court of final review for a payload. By its acceptance of the principal investigators and their instruments, it certifies that, up to this stage, the user requirements have been properly incorporated into the systems engineering process for the mission. After the members of the Committee complete their review, the chairperson sends their recommendations to the associate administrator of the Office of Space Science and Applications who approves the investigators. After approval of the investigators by the associate administrator, the only way to change an investigator or an instrument is to appeal over the head of the associate administrator, to the deputy administrator or the administrator of NASA. Only once in the past 30 years has the decision of an associate administrator been reversed. In that case, NASA modified its selection procedure to facilitate the selection of investigators for the Apollo-Soyuz Mission. The chairperson of the Space Science Board objected to the change; NASA redid its selection and followed the normal procedure.

THE ASSOCIATE ADMINISTRATOR'S APPROVAL

After the associate administrator approves the principal investigators, each of them is sent a letter to inform them of their selection and to give them any guidelines or qualifications that come from the selection process. For instance, only a part of the investigator's proposal may have been approved or the investigator may have agreed to provide environmental data to other investigators on the mission to aid them in the interpretation of their data. Funding for the mission may be limited; the associate administrator may direct each investigator to control costs very carefully and request that some aspect of the investigation be modified or excluded if it becomes apparent that the costs will exceed the funds allocated for the investigation. If the interest in the mission is high and the funds are limited or the resources of the spacecraft, such as the weight, power and telemetry, are very constrained, the associate administrator may give provisional approval to one or more investigators pending an analysis by the project to determine if the resources are available.

The associate administrator's letter to a principal investigator is an informal contract between the associate administrator and the principal investigator that obligates the investigator to devote the time and energy required to accomplish the objectives of the investigation. It obligates the associate administrator to proceed with the mission and provide the resources and assistance that the principal investigator will need.

At the same time the letters are sent to the principal investigators, the associate administrator also sends a letter to the director of the Center responsible for managing the project. This letter notifies the director of the investigators selected and the qualifications or guidelines that have been given. The letter is accompanied by the authorization and transfer of funds that enable the project team to negotiate contracts with and fund

the work of the principal investigators. This contract should provide for the support of the principal investigator and specify the work to be done during design, manufacture, pre-flight testing, operations, analysis of the data and publication of the results. The funding for data analysis is normally carried in a separate line item in the Space Science budget and is transferred to the Center through a separate channel at a later date. Regardless of how the funding for the operational phase is handled, the associate administrator should require that the project team provide for data analysis and publication of the results in these contracts with the principal investigators. The incorporation of the user requirements into the systems engineering process will not be complete unless all phases of the mission are considered, including data analysis, interpretation and publication of the results.

The Space Science Steering Committee's review and the associate administrator's approval of the principal investigators complete those phases of the mission that are led by the division director at NASA Headquarters. Once the investigators have been selected, the focus of the work shifts from Headquarters to the Center, where the project manager and the project scientist take over the technical and scientific leadership of the mission. They are responsible for the final steps in the incorporation of the users requirements into the systems engineering process.

ASSESSMENT OF THE PRINCIPAL INVESTIGATORS

When the associate administrator for the Office of Space Science and Applications selects the principal investigators and authorizes the Center to negotiate contracts with them, the responsibility for working with the scientists is transferred from the division director and the program scientists at Headquarters to the project manager and the project scientists at the Center. Receipt

of the letter triggers an intensive assessment by the project manager of each investigator and of the status of each instrument. This assessment should be completed prior to the beginning of preliminary design activity.

The assessment is conducted by a team appointed by the project manager. The team consists of several engineers from the Center. A key member of the project manager's review team is the project scientist, who, among other tasks, serves as the communication link between the investigators and the project team.

THE ROLE OF THE PROJECT SCIENTIST

The Center director, with concurrence of the Office of Space Science and Applications associate administrator, appoints the mission's project scientist. This project scientist has a powerful role during a scientific mission, quite different from that of the project manager and, at this stage, equally important. If the project scientist and the project manager have a conflict they cannot resolve and that may affect the mission's scientific outcome, the project scientist is expected to carry the case to Center management and, if it is a good case, to prevail.

The project scientist should have as vested an interest in the scientific success of the mission as the one who conceived the mission or as an investigator on the mission. As an experienced space scientist and person who has conducted investigations in space, the project scientist should understand what information the project needs from the principal investigator in order to conduct the mission and should be able to accurately communicate those requirements, and the reasons for them, to the scientists. The project scientist should understand the technical requirements submitted by the principal investigators and be able to communicate them to the project. In addition, the project scientist should be able to judge which of the requirements of the principal investigator are mandatory and which are only highly

desirable so that the resources of the project are not squandered. Conversely, the project scientist should be able to sort out the highly desirable from the mandatory requirements of the project manager so that unnecessary constraints, reporting requirements or reviews are not placed on the principal investigators. Clearly, the project scientist must have the confidence of the project manager and the investigators on the mission in order to succeed. The assessment of the principal investigators provides an excellent opportunity for the project scientist to become a reliable representative of the scientists to the project team and of the project team to the scientists.

People ask, why all this concern about the communication channel between the project and the investigators? Why can't the project manager deal with the investigators just as one would with the person responsible for any other subsystem on the spacecraft? Early experience in space science showed that a project manager who was not a scientist, or who did not have a strong competent project scientist working with him or her, usually got into one of two kinds of trouble. Either the project manager regarded the scientists as all powerful and gave in to all their whims, thereby driving the costs of the mission out of sight, or the project manager regarded the scientists as overly bright children and overrode their legitimate requests, thus causing their instruments to fail or forcing the scientists to complain to Center management or NASA Headquarters and try to get the project manager replaced.

FACT FINDING

The initial assessment of each principal investigator by the project team is the most important part of the incorporation of the user requirements into the systems engineering process of a mission. The primary purpose of the assessment is to determine the technical requirements of the instruments and their compatibility with each other and with the

spacecraft and the operational equipment. In addition, it provides the project manager with the first opportunity to determine the experience and capability of each principal investigator and of the team, and to assess whether the investigator's institution can and will provide the support that will be needed.

The assessment begins with "fact finding," a systematic effort by the review team to collect information about the investigators. The team conducts its review at the investigator's institution, rather than bringing the investigator and the team to the Center. A visit to the institution enables the review team to not only examine the laboratory model of the instrument, but also to review the calculations and test results that support the design. The team can review the facilities that will be available to investigators to develop, test and calibrate the flight instruments. If the investigator plans to have most of the work done by a contractor, then the review team conducts a similar review at the contractor's plant.

The review should cover all the elements that are required by the investigator to complete the objectives of the experiment. By "all the elements," I mean all the pieces of hardware, all the facilities, all the testing gear that will be required, and all the work and the people that will be required to enable the investigator to design, build, test and fly the instrument. In addition, the review should identify all the computers, all the programs and all the software that the investigator will require to analyze the data and publish the results. The review should cover the entire mission, from design and development, to testing and calibration, to placement of the published results and of the data in the archives. The plans, scheduled actions and funding requirements as a function of time are key elements to be reviewed. The impact of project requirements on the investigator or the instrument should be covered in the review. Throughout the review, its two-way nature must be emphasized. The

purpose of the review is to determine what the investigator requires of the project and to inform the investigator of the requirements of the project.

The review begins with information and data collection by the team. The team must collect information on the technical resources on the spacecraft that the instrument requires such as weight, telemetry, band width, volume, power, commands and thermal control.

The team must collect data on the engineering constraints imposed by the instrument on the spacecraft, including but not limited to:

- Location of the instrument
- Look angle and field of view
- Pointing and stabilization required
- Operational requirements
- Special treatment during testing, launch, and operations
- Limitations on vibration and shock
- Limitations on stray electromagnetic fields
- Limitations on material surrounding the instrument
- Limitations on outgassing.

The team needs to know the facilities that will be required by the instrument and their availability, either at the investigator's institution, the contractor, or at the field center or its contractors, including but not limited to:

- Vacuum chambers
- Shock and vibration tables
- Solar simulators
- Computers
- Special test and calibration facilities
- Special data handling and analysis facilities.

The team must collect information and plans for the funding, manpower and management capability that will be required by the inves-

tigator at the host institution and by the project team to monitor the work of the investigator.

Obviously, not all of this data will be available at this first review. However, where information is not available, the need should be established and the project manager and the principal investigator must formulate a mutually acceptable plan as to who will generate the information and on what schedule.

This initial data gathering phase provides an excellent opportunity for the project manager and the systems engineers to assess the capability of the principal investigator and the team. NASA policy makes the principal investigator, responsible for all phases of the investigation, beginning with the design of the instrument, continuing through to the delivery of a calibrated, tested and flight worthy instrument, and culminating in the publication of the results. During the review, the principal investigator should demonstrate understanding and the ability to discharge this responsibility and should be able to describe how to conduct the day-by-day work of the team. The principal investigator should state whether the day-by-day work of the team will be under the investigator's direction or whether a manager will be appointed to direct the work. If a manager is appointed, do the principal investigator, the manager and the project manager all understand the limits of the authority of the manager? What decisions can be made by the manager and which ones must go to the investigator? Has the investigator delegated sufficient authority to the manager so that decisions can be made and the work can be kept on schedule? How does the principal investigator plan to oversee the work of the manager? Does the investigator plan to attend certain key reviews to see how things are going? Will the manager give weekly reports?

The project manager and the principal investigator should agree on which reviews the investigator will attend and which can

be delegated to the manager. They also need to agree on how they will resolve disputes that will arise between the principal investigator's manager and the project manager.

If the principal investigator plans to handle the day-to-day operations, another set of questions needs to be asked. Is the investigator prepared and able to spend the time and energy to handle the daily work? Is the investigator prepared to travel to the Center or to a contractor when reviews must be held and decisions need to be made? Is the investigator prepared to give up other research during the development of the instrument?

Appointing a good project manager is generally better for the investigator and the team. The project manager can concentrate on the daily activity of managing the team and the investigator can focus on meeting the requirements that will be levied by the project manager and the team.

The review team needs to ask other questions. Is the investigator's team adequate for the task? Have they planned their work and laid out a sensible schedule? Are they cooperative and forthright about the status of their instrument? Are the kinds of engineers and technicians that will be needed either on the investigator's team or at the contractor? Has the investigator done a good job estimating the costs as a function of time? Has a reserve been allowed for unforeseen problems, and if so, have criteria and a schedule been laid out for its use? Any weakness in planning or management at this stage, if not corrected, will inevitably result in more serious problems later in the project.

The analysis of the strengths and weaknesses of a principal investigator's team serves an important function in the incorporation of the user requirements into the systems engineering process. If an investigator has a competent team and adequate facilities and equipment, the project manager can reduce the monitoring requirements for that investigator. The investigator can reduce the time allocated for testing and integration and may waive certain tests. On

the other hand, if the investigator has a weak team or inadequate facilities, then the project manager has to lay out a project plan and a schedule that takes this weakness into account. Additional money must be set aside to cover overruns. Provisions for additional monitoring must be made and additional time for testing and integration must be allowed. An engineer from the project may be assigned to aid the investigator. The investigator is placed on the list of the project's "Top Ten Problems," thereby alerting the Center management and Headquarters of the problem. Any management or technical problems unearthed in this initial assessment should be treated just as thoroughly and just as promptly as the failure of any subsystem would be treated later in the schedule. Prompt action at this stage will prevent many hardware problems from arising later when there is less time and less money to resolve them.

The review of each principal investigator culminates in the negotiation of a contract between the Center and principal investigator, whereby the investigator is to produce a flight instrument using funds provided by the Center. At the conclusion of the assessment process, a principal investigator will have two contracts: one with the associate administrator of the Office for Space Science and Applications to accomplish the objectives of the experiment proposed, and the other with the project management center to produce an instrument that is ready for flight. A principal investigator who thinks that a Center decision will jeopardize the investigation has the right to appeal the decision directly to the associate administrator of the Office for Space Science and Applications. This appeal channel is rarely, if ever, used.

THE SYSTEMS ENGINEERING PROCESS

Once the review team has completed its fact finding and its assessment of the investigator's capability, the systems engineers are

ready to complete the conventional systems analysis of the system. The information the review team has collected enables them to incorporate the user requirements into that process.

By this time, all the broad boundaries of the mission are established; the investigators have been selected, a preliminary design of the spacecraft is available, the transportation system is specified, the total cost of the mission has been set (or a ceiling placed on the total cost) and a preliminary launch date scheduled.

If there is no hard fast launch date, then the launch schedule may become a variable in the systems analysis and shifted forward or back to reduce costs or improve the scientific return of the mission. If it is a planetary mission, however, the launch date is not a variable but is rigorously set by planetary dynamics; the role of the systems engineer is to identify the decisions that must be made and the actions that must be taken to assure the sanctity of that launch date.

In the case of a high priority scientific mission, such as Viking or the Hubble Space Telescope, the scientific objectives may be the primary constraint. The systems engineer can adjust the launch vehicle, the launch date and the total cost to meet the scientific objectives.

For most missions, however, the primary constraints will be technical and financial. The launch vehicle may be specified; there may be a cap on the funding, certain subsystems may be specified and in many cases the spacecraft itself will be specified. In such highly constrained missions, the only variables the systems engineer has to work with are the number and complexity of the scientific instruments that can be accommodated. For such highly constrained missions, the associate administrator of the Office of Space Science and Applications will usually select a core payload that is certain to be accommodated and then add one or more investigations to be included if the systems analysis shows they can be accommodated.

In this highly constrained case, the systems engineer takes the requirements of the core payload and the existing constraints and, working closely with the project scientist and the principal investigators, makes a number of tradeoff studies to determine the maximum number of investigations that can be accommodated and the maximum amount of scientific information that can be collected.

The objective of the systems engineering effort at this stage is to plan the entire mission, establish the specifications for the instruments and the spacecraft, lay out a schedule for all the activities of the mission, establish milestones for completion of major activities, schedule the testing and integration work, set a launch date, estimate the cost and lay out a funding plan for the entire mission. The systems engineers identify any technical conflicts that exist between instruments or between an instrument and the spacecraft. Where they find conflicts, they identify the options available to the project to solve them, conduct tradeoffs between the options and recommend the option that they think will produce the greatest scientific return for the lowest cost.

As the systems engineers conduct their analyses, there is a continuous iteration process that takes place throughout the project and among the investigators. Different locations of the instruments on the spacecraft are studied and discussed with the investigators to determine which are best. Tradeoffs may have to be made between the value of adding an investigation and adding more power or more telemetry bandwidth for the core payload. In rare instances, the systems analysis may show that additional resources are available on the spacecraft; then tradeoffs are made to determine how to allocate the resources among the investigators to better accomplish the scientific objectives.

Many complicated tradeoffs are made at this stage in a project. As an example, systems engineers working closely with the project scientist and the investigators may

conduct tradeoffs to determine how much data processing should be done on board by each instrument, thereby increasing the weight and power required by the instruments but reducing the complexity of, and the weight and power required by, the communications system of the spacecraft.

Mutually acceptable schedules for the use of common ground facilities such as shake tables, vacuum chambers and calibration equipment are worked out between the project, the investigators and the persons responsible for those facilities. A detailed schedule of all the tests, calibration runs and flight operations is established with each investigator. These schedules, as emphasized repeatedly in this paper, should carry through flight operations and data analysis. Only by doing this can a systems engineer be sure that all the requirements of the scientists have been incorporated into the mission plan. By forcing the occasionally unwilling investigator to sit down and think through the entire experiment, the systems engineer may bring to the surface a major technical problem or an inadequate cost estimate.

Once the entire mission is laid out, the investigators accommodated, their expenses estimated and a launch date established, the systems engineer must estimate how much and what kind of resources need to be reserved for unanticipated problems. Extra slack time must be placed in the schedule to accomplish unanticipated work. The systems engineer must reserve some weight, power and communications capability for shortages that will inevitably arise. Funds to cover overruns must be reserved and a schedule by which the funds are to be released must be prepared. If there is no schedule for the release of reserve funds, then they may all be used up in the early months of the project, leaving nothing for the major problems that will occur later.

The project manager and the overseers at the Center and Headquarters should examine any deviation by an investigator from the planned use of the reserves with the same

care they would examine an instrument that is not meeting its design specifications or its milestones. Such a deviation in the rate of use of reserves may identify a weakness in the investigator's team or in the design of the instrument early in the development cycle. If the project manager takes prompt action when an unexpected use of the reserves is first seen, technical or schedule problems that may occur later in the development phase can be eliminated or reduced.

At this time, the project manager establishes another important policy—how the information about the reserves will be treated. The project manager can choose to operate somewhere between two extremes: "everything on the table" or "hold all the cards close to the chest." In the first extreme, everybody in the project is informed, including all the subsystem managers, all the principal investigators and the contractors, exactly what the reserves are, who is holding them and the schedule for their use. At the other extreme, the project manager treats the reserves as highly classified information known only to the project manager and possibly some of the senior management. Both extremes have worked. The choice largely depends on the experience and personality of the project manager and NASA's current management philosophy. A new, insecure or weak project manager may want to keep this information confidential to help control the project. A more confident project manager may choose to operate an open system. If a project manager chooses to operate an open system, there must be a willingness to accept a high level of acrimony in the project. A principal investigator fighting a weight problem or overrunning the budget will eye a compatriot's reserve and scheme to get it. On the other hand, by operating in an open manner the project manager may create a more healthy climate of trust between the investigators and the project team and thereby discover problems earlier than if all the reserves are kept secret. Sharing knowledge of the problems and the reserve being

maintained can help a project manager promote teamwork on the project, raise the morale, and encourage the investigators to carefully manage their reserves. On the other hand, if NASA's current policy is to pull all identifiable reserves into a Headquarters reserve to be held by the comptroller, then project managers will instinctively bury any financial reserves somewhere in the project.

Ultimately, the user requirements will be assimilated into the systems engineering process, the preliminary designs will be completed, the schedules established, and the rate of expenditure established. When this is done, the project is ready for its first major design review, the preliminary design review.

PRELIMINARY DESIGN REVIEW

The Preliminary Design Review (PDR) ends the preliminary design work, and completes the incorporation of user requirements into the systems engineering process. All aspects of the mission and all future activities required to accomplish the mission should be planned by this time.

The choice of a chairperson for the PDR depends upon the complexity, cost and national interest in the project. The division director may chair the PDR of a routine, small scientific project. The associate administrator for the Office of Space Science and Applications will chair the PDR of a larger, more complex mission. The administrator or deputy administrator of NASA may chair the PDR of a large, complex, costly, highly visible mission such as the Hubble Telescope, or Earth Observing System. The chairperson should be someone who thrives on crowds and controversy and has a vast curiosity about the mission and a penchant for uncovering unforeseen or concealed problems. The chairperson should use the PDR to identify and resolve any issues that the project team or the investigators may have overlooked or may be trying to avoid.

The good chairperson goes around the room after the discussion of a controversial item and questions the key people involved to see if they all understand and agree on the project's plan. The chairperson of the PDR cannot be a "shrinking violet" or an introvert (at least not during a PDR).

The project manager conducts the review. Attendance from Headquarters includes, but is not be limited to: the associate administrator for the Office of Space Science and Applications or a designee, the division director, the program manager, the program scientist, the financial analyst, the NASA comptroller or the designee, and the associate administrators for the Offices of Space Flight and Operations or their designees. Someone from the Office of International Affairs attends if there are foreign investigators or if it is a joint mission with another country. Attendance from the Center will include the director, the financial analysts, representatives of the engineering disciplines and the systems engineers. All the principal investigators attend. Senior people from the major contractors also attend. If the PDR is for an applications mission, then senior people from the agency who will use the system will attend.

The chairperson expects the project manager to present a clear, concise statement of the overall objectives of the mission. If there are other nonscientific objectives for the mission—if, for instance, one of the objectives is to test a new subsystem, a new spacecraft or a new tracking system—then the project manager is expected to clearly specify the relationship and priorities between those other objectives and the scientific objectives. The chairperson should make sure that all objectives are clear, understood and agreed to by the attendees.

The project manager should present a complete schedule, extending from the PDR through the Critical Design Review, on through development, testing and calibration of the instruments and continue on to

launch operations, data analysis and publication or use of the results. Slack time should be clearly shown. Even though detailed plans for operation and data analysis may not be complete at this time, the systems engineering process should have produced a list of the facilities required and a schedule for their use. Very often, the examination of the mission's schedule at the PDR will uncover potential conflicts for the use of facilities or an underestimate of the cost of some phase of the mission.

The chairperson reviews the status of each instrument. Ideally, the review of an instrument will consist of two parts, a presentation by the principal investigator followed by the project scientist's assessment of the status of the instrument. The principal investigator should describe the experiment, its objectives and how they relate to the objectives of the mission. The principal investigator should describe the instrument, show the schedule and slack times, and present a cost breakdown and a funding schedule. The investigator should identify any issues with the project manager, including any foreseeable technical and procurement problems, and list the top four or five problems. The project scientist should then give the project's view of the status of the instrument and should state whether the project agrees with the status as presented by the investigator. The project scientist should present any concerns the project has about the principal investigator, the team, the institution or the contractor.

This review by the project scientist at the PDR should not lead to a confrontation between the principal investigator and the project scientist or the project manager; through earlier discussions, each should be aware of what the other intends to say; each should be aware of the concerns of the other and at the review they should present a jointly developed plan to solve the problems that exist. The project manager and the principal investigator should understand and accept the actions that the other intends to take to

resolve the problems. If the investigator has only a tentative approval to fly on the mission, then the actions and milestones should be specified that will lead to final acceptance or rejection.

The project manager or the manager's designee should review the status of the other elements of the mission, their schedules and problems. If the cost or configuration of a subsystem is being determined by a requirement of a particular investigation, that fact should be presented so that senior management and the principal investigator can decide whether the particular aspect of the investigation merits the additional cost or complexity.

The project team should present an overall assessment of the instruments and their interaction with each other and with the subsystems on the spacecraft. The project manager may elect to divide the experiments into two groups: one group consisting of those investigations in which the design of the instrument is on schedule, within budget, and the investigator is not in need of careful monitoring; the second group consisting of those instruments that have major problems, that will require careful monitoring and perhaps even a backup instrument.

The project manager should review the status of the resources available to the project, the reserves that are being held and the schedule for their release. At the conclusion of the PDR, the project manager should identify the top 10 problems for the overall project and describe plans to resolve them.

At the conclusion of the PDR, all the participants—Headquarters, Center management, the project team, the principal investigators and the subsystem managers—should all understand and accept the status and requirements of the investigations scheduled for the mission. The principal investigators should agree with the status of their experiment as presented, and they should understand and be prepared to accept the requirements and meet the schedules that have been placed on them by the project.

Once the actions that were assigned to the project and the investigators by the PDR have been completed, the requirements of the investigators should be incorporated into the systems engineering process. The project team and the investigators are then ready to proceed with the detailed design and manufacture of the instruments and the spacecraft.

The majority of the systems engineering effort required to incorporate the user requirements should be complete at this time. Normal project management and engineering techniques should be adequate to complete the integration of the investigators into the mission. There will, however, be a continuing need for systems engineers to support the project team. No matter how good and how complete the systems engineering effort has been, and how carefully the PDR is conducted, problems will still be encountered in the instruments or in the subsystems and changes will have to be made. The systems engineer will have to trace the impact of those changes through the system, identify the problems that are created and provide the options for their solution. Inevitably, there will be a shortage of resources available—additional power or weight required—and the systems engineer will have to assess the system to see how the resources can be found and analyze the impact of using those resources. Occasionally, excess resources will become available; the systems engineer will have to examine these extra reserves and determine how they can best be applied to enhance the quality of the mission.

As the work progresses, the engineers will eventually understand the instruments and their spacecraft, their designs will be frozen, all the options will be eliminated and the systems engineer will no longer be needed. Sometime before this stage is reached, the good systems engineers will become bored and will move on to a new system with new challenges.

GLOSSARY

Mission. An effort to increase human knowledge that requires the launch of one or more spacecraft. A mission begins with the initial concept and concludes with the publication of the results.

System. All the tasks and all the equipment, both ground and space based, required to accomplish a mission.

Systems engineering. The systematic planning activity that begins with the mission objectives and the requirements of the scientists and turns them into specifications for hardware and facilities, conducts tradeoff studies between competing subsystems, analyzes the interaction between the subsystems to eliminate unwanted interference, and prepares schedules, cost estimates and funding plans.

Program. The formulation and documentation of a mission prepared by NASA Headquarters and used to obtain authorization and funding from Congress to conduct the mission.

Project. All the equipment produced or purchased by, and all the activity conducted and directed by, a NASA Center to accomplish a mission.

Division director. An individual at NASA Headquarters responsible for a group of related scientific programs.

Program manager. A person, usually an engineer, at NASA Headquarters in charge of a program. A program manager reports to a division director.

Program scientist. A scientist at NASA Headquarters responsible for formulating the scientific objectives of a program. A program scientist reports to a division director.

Project manager. The person, usually an engineer, at a NASA Center who is responsible for the success of a project. The project manager reports to the senior management of the Center.

Project scientist. The scientist at a NASA Center responsible for accomplishing the

scientific objectives of a project. The project scientist reports to the senior management of the Center.

Principal investigator. A scientist, selected by NASA Headquarters, to conduct an experiment during a mission.